Method of analyzing a subterranean formation traversed by a wellbore. The method uses a tool comprising a transmitter antenna and a receiver antenna, the subterranean formation comprising one or more formation layers. The tool is suspended inside the wellbore, and one or more electromagnetic fields are induced in the formation. One or more time-dependent transient response signals are detected and analyzed. Electromagnetic anisotropy of at least one of the formation layers is detectable. Geosteering cues may be derived from the time-dependent transient response signals, for continued drilling of the wellbore until a hydrocarbon reservoir is reached. The hydrocarbon may then be produced.
\[ \hat{\theta} = (\sin \delta \cos \phi, \sin \delta \sin \phi, \cos \delta) \]

\[ \hat{\psi} = (\sin \delta \cos (\phi - \psi), \sin \delta \sin (\phi - \psi), \cos \delta) \]
FIG. 17

\[ \sigma_1 = 1 \text{ S/m} \]
\[ \sigma_2 = 0.1 \text{ S/m} \]

FIG. 10

\[ D_1 = 10 \text{ m} \]
**FIG. 20**

- $\sigma_2/\sigma_1$

- $\sigma_{app}(t \to \infty)/\sigma_1$

**FIG. 21**

- $\sigma_{app}(t)(S/m)$

- $t_c$

- $t_c$

- $D = 1m; L = 1m$
- $D = 5m; L = 5m$
- $D = 1m; L = 5m$
- $D = 50m$
- $D = 5m; L = 1m$
FIG. 26

FIG. 27

\[ \sigma_{opp}(t) \text{ (S/m)} \]

- \( D = 1 \text{m} \)
- \( D = 5 \text{m} \)
- \( D = 10 \text{m} \)
- \( D = 25 \text{m} \)
- \( D = 50 \text{m} \)
- \( D = 100 \text{m} \)
- \( D = 200 \text{m} \)
FIG. 28

FIG. 29
FIG. 30

FIG. 31
METHOD OF ANALYZING A SUBTERRANEAN FORMATION AND METHOD OF PRODUCING A MINERAL HYDROCARBON FLUID FROM THE FORMATION

CROSS REFERENCE TO EARLIER APPLICATION

[0001] The present application claims benefit under 35 USC § 119(e) of U.S. Provisional application No. 60/797, 556 filed 4 May 2006.

FIELD OF THE INVENTION

[0002] In one aspect, the present invention relates to a method of analyzing a subterranean formation traversed by a wellbore. In another aspect the invention relates to a method of producing a mineral hydrocarbon fluid from an earth formation. In still another aspect, the invention relates to a computer readable medium storing computer readable instructions that analyze one or more electromagnetic response signals.

BACKGROUND OF THE INVENTION

[0003] In logging while drilling (LWD) geo-steering applications, it is advantageous to detect the presence of a formation anomaly ahead of or around a bit or bottom hole assembly. There are many instances where “Look-Ahead” capability is desired in LWD logging environments. Look-ahead logging comprises detecting an anomaly at a distance ahead of a drill bit. Some look-ahead examples include predicting an over-pressured zone in advance, or detecting a fault in front of the drill bit in horizontal wells, or profiling a massive salt structure ahead of the drill bit.

[0004] In U.S. Pat. No. 5,955,884 to Payton, et al, a tool and method are disclosed for transient electromagnetic logging, wherein electric and electromagnetic transmitters are utilized to apply electromagnetic energy to a formation at selected frequencies and waveforms that maximize radial depth of penetration into the target formation. In this transient EM method, the current applied at a transmitter antenna is generally terminated and a temporal change of voltage induced in a receiver antenna is monitored over time.

[0005] When logging measurements are used for well placement, detection or identification of anomalies can be critical. Such anomalies may include for example, a fault, a bypassed reservoir, a salt dome, or an adjacent bed or oil-water contact.

[0006] U.S. patent applications published under Nos. 2005/0092487, 2005/0093546, 2006/0038571, each incorporated herein by reference, describe methods for localizing such anomalies in a subterranean earth formation employing transient electromagnetic (EM) reading. The methods particularly enable finding the direction and distance to a resistive or conductive anomaly in a formation surrounding a borehole, or ahead of the borehole, in drilling applications.

[0007] Of the referenced U.S. patent publication, US 2006/0038571 shows that transient electromagnetic responses can be analyzed to determine conductivity values of a homogeneous earth formation (single layer), and of two or three or more earth layers, as well as distances from the tool to the interfaces between the earth layers.

SUMMARY OF THE INVENTION

[0008] In principle, the methodology as set forth in US 2006/0038571 would work for any number of layers. However, the larger the number of layers, and particularly when the layers are thin, the more complicated the analysis is. For instance, a thinly laminated sand/shale sequence would be difficult to analyze employing the methodology as set forth in US 2006/0038571.

[0009] In accordance with the invention there is provided a method of analyzing a subterranean formation traversed by a wellbore, using a tool comprising a transmitter antenna and a receiver antenna, the subterranean formation comprising one or more formation layers and the method comprising:

[0010] detecting a transient electromagnetic response signal from the electromagnetic field, employing the receiver antenna,

[0011] detecting a transient electromagnetic response signal from the electromagnetic field, employing the receiver antenna,

[0012] detecting a transient electromagnetic response signal from the electromagnetic field, employing the receiver antenna,

[0013] detecting a transient electromagnetic response signal from the electromagnetic field, employing the receiver antenna.

[0014] The electromagnetic properties of a formation layer comprising a number of thin layers may be approximated by one formation layer comprising an electromagnetic anisotropy. It is thereby avoided to have to take into account each thin layer individually when inverting the responses.

[0015] Amongst other advantages of taking into account electromagnetic anisotropy, is that anisotropy information may be useful in precisely locating mineral hydrocarbon fluid containing reservoirs, as such reservoirs are often associated with electromagnetic anisotropy of formation layers.

[0016] The result of the analyzing step mentioned above may be outputted, including displayed or stored or transmitted or otherwise made conveyed and made available to an operator or a geosteering system. Such a geosteering system may use the result of the analysis to generate a geosteering cue in response. The geosteering cue may in itself be outputted, including displayed or stored or transmitted or otherwise made conveyed and made available to an operator and/or used to continue drilling in response to the geosteering cue.

[0017] Said method of analyzing a subterranean formation may be used in a geosteering application, wherein a geosteering cue may be derived from the one or more time-dependent transient response signals, taking into account electromagnetic anisotropy, and wherein a drilling operation may be continued in accordance with the derived geosteering cue in order to accurately place a well.

[0018] Thus, in another aspect there is provided a method of producing a mineral hydrocarbon fluid from an earth formation, the method comprising steps of:

[0019] drilling a well bore in the earth formation;

[0020] inducing an electromagnetic field in the earth formation employing the transmitter antenna;

[0021] detecting a transient electromagnetic response signal from the electromagnetic field, employing the receiver antenna;
deriving a geosteering cue from the electromagnetic response;
continue drilling the well bore in accordance with the geosteering cue until a reservoir containing the hydrocarbon fluid is reached;
producing the hydrocarbon fluid.
In still another aspect, the invention provides a computer readable medium storing computer readable instructions that analyze one or more detected time-dependent transient electromagnetic response signals that have been detected by a tool suspended inside a wellbore traversing a subterranean formation after inducing one or more electromagnetic fields in the formation, wherein the computer readable instructions take into account electromagnetic anisotropy of at least one formation layer in the subterranean formation.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described in more detail below by way of examples and with reference to the attached drawing figures, wherein:

FIG. 1A is a block diagram showing a system implementing embodiments of the invention;
FIG. 1B schematically illustrates an alternative system implementing embodiments of the invention;
FIG. 2 is a flow chart illustrating a method in accordance with an embodiment of the invention;
FIG. 3 is a graph illustrating directional angles between tool coordinates and anomaly coordinates;
FIG. 4A is a graph showing a resistivity anomaly in a tool coordinate system;
FIG. 4B is a graph showing a resistivity anomaly in an anomaly coordinate system;
FIG. 5 is a graph illustrating tool rotation within a borehole;
FIG. 6 schematically shows directional components involving electromagnetic induction tools relative to an electromagnetic induction anomaly;
FIG. 7 is a graph showing the voltage response from coaxial $V_{cc}(t)$, coplanar $V_{cc}(t)$, and the cross-component $V_{cc}(t)$ measurements for $L=1 m$, for $\theta=30^\circ$, and a distance $D=100 m$ from a salt layer;
FIG. 8 is a graph showing the voltage response from coaxial $V_{cc}(t)$, coplanar $V_{cc}(t)$, and the cross-component $V_{cc}(t)$ measurements for $L=1 m$, for $\theta=30^\circ$, and a distance $D=100 m$ from a salt layer;
FIG. 9 is a graph showing apparent dip $\theta_{app}(t)$ for an arrangement as in FIG. 7;
FIG. 10 is a graph showing apparent conductivity $\sigma_{app}(t)$ calculated from both the coaxial $V_{cc}(t)$ and the coplanar $V_{cc}(t)$ responses for the same conditions as in FIG. 9;
FIG. 11 is a graph showing apparent dip $\theta_{app}(t)$ for the $L=1 m$ tool assembly when the salt face is $D=10 m$ away, for various angles between the tool axis and the target;
FIG. 12 is a graph similar to FIG. 11 whereby the salt face is $D=50 m$ away from the tool;
FIG. 13 is a graph similar to FIG. 11 whereby the salt face is $D=100 m$ away from the tool;
FIG. 14 is a schematic illustration showing a coaxial tool with its tool axis parallel to a layer interface;
FIG. 15 is a graph showing transient voltage response as a function of $t$ as given by the coaxial tool of FIG. 14 in a two-layer formation at different distances from the bed;
FIG. 16 is a graph showing the voltage response data of FIG. 15 in terms of the apparent conductivity $\sigma_{app}(t)$;
FIG. 17 is similar to FIG. 16 except that the resistivities of layers 1 and 2 have been interchanged;
FIG. 18 shows a graph of the $\sigma_{app}(t)$ for the case $D=1 m$ and $L=1 m$, for various resistivity ratios while the target resistivity is fixed at $R_2=1 \Omega m$;
FIG. 19 shows a comparison of apparent conductivity at large values of $t$, $\sigma_{app}(t-\infty)$, for coaxial responses where $D=1 m$ and $L=1 m$ as a function of conductivity $\sigma_2$ of the target layer while the local conductivity $\sigma_1$ is fixed at 1 S/m;
FIG. 20 graphically shows the same data as FIG. 19 plotted as the ratio of target conductivity over local layer conductivity $\sigma_1$ versus ratio of the late time apparent conductivity $\sigma_{app}(t-\infty)$ over local layer conductivity $\sigma_1$;
FIG. 21 shows a graph containing apparent conductivity $\sigma_{app}(t)$ versus time for various combinations of $D$ and $L$;
FIG. 22 graphically shows the relationship between ray-path RP and transition time $t$;
FIG. 23 is a schematic illustration showing a coaxial tool approaching or just beyond a bed boundary;
FIG. 24 is a graph showing transient voltage response as a function of $t$ as given by the coaxial tool of FIG. 23 at different distances $D$ from the bed;
FIG. 25 is a graph showing the voltage response data of FIG. 24 in terms of the apparent conductivity $\sigma_{app}(t)$;
FIG. 26 is similar to FIG. 25 except that the resistivities of layers 1 and 2 have been interchanged;
FIG. 27 presents a graph comparing $\sigma_{app}(t)$ of FIG. 25 and FIG. 26 relating to $D=1 m$;
FIG. 28 shows a graph of $\sigma_{app}(t)$ on a linear scale for various transmitter/receiver spacings $L$ in case $D=50 m$;
FIG. 29 graphically shows distance to anomaly ahead of the tool versus transition time ($t_3$) as determined from the data of FIG. 25;
FIG. 30 schematically shows a coplanar tool approaching or just beyond a bed boundary;
FIG. 31 is a graph showing transient voltage response data in terms of the apparent conductivity $\sigma_{app}(t)$ as a function of $t$ as provided by the coplanar tool of FIG. 30 at different distances $D$ from the bed;
FIG. 32 shows a comparison of the late time apparent conductivity $\sigma_{app}(t-\infty)$ for coplanar responses where $D=50 m$ and $L=1 m$ as a function of conductivity $\sigma_1$ of the local layer while the target conductivity $\sigma_2$ is fixed at 1 S/m;
FIG. 33 graphically shows the same data as FIG. 32 plotted as the ratio of target conductivity $\sigma_2$ over local layer conductivity $\sigma_1$ versus ratio of the late time apparent conductivity $\sigma_{app}(t-\infty)$ over local layer conductivity $\sigma_1$;
FIG. 34 graphically shows distance to anomaly ahead of the tool versus transition time ($t_3$) as determined from the data of FIG. 31;
FIG. 35 schematically shows a model of a coaxial tool in a conductive local layer (1 $\Omega m$), a very resistive layer (100 $\Omega m$), and a further conductive layer (1 $\Omega m$);
FIG. 36 is a graph showing apparent resistivity response versus time, $R_{app}(t)$, for a geometry as given in FIG. 35 for various thicknesses $\Delta$ of the very resistive layer; FIG. 37 schematically shows a model of a coaxial tool in a resistive local layer (10 $\Omega$m), a conductive layer (1 $\Omega$m), and a further resistive layer (10 $\Omega$m); FIG. 38 is a graph similar to FIG. 36, showing apparent resistivity response $R_{app}(t)$ versus time for a geometry as given in FIG. 37 for various thicknesses $\Delta$ of the conductive layer; FIG. 39 schematically shows a model of a coaxial tool in a conductive local layer (1 $\Omega$m) in the vicinity of a highly resistive layer (100 $\Omega$m) with a separating layer having an intermediate resistance (10 $\Omega$m) of varying thickness in between; FIG. 40 is a graph similar to FIG. 36, showing apparent resistivity response versus time, $R_{app}(t)$, for a geometry as given in FIG. 39 for various thicknesses $\Delta$ of the separating layer; FIG. 41 shows calculated coaxial transient voltage responses for an $L=1$ m tool in an anisotropic formation wherein $\sigma_{c}=1$ S/m ($R_{c}=1$ $\Omega$m) for various values of $\beta^2$; FIG. 42 shows apparent conductivity based on the responses of FIG. 41; FIG. 43 shows apparent conductivity based on coaxial responses for an $L=1$ m tool in a formation wherein $\sigma_{c}=0.1$ S/m for various values of $\beta^2$; FIG. 44 shows apparent conductivity based on coaxial responses for an $L=1$ m tool in a formation wherein $\sigma_{c}=0.01$ S/m for various values of $\beta^2$; FIG. 45 shows a graph plotting late time asymptotic value of coaxial apparent conductivity $\sigma_{c}(t\rightarrow\infty)$ from FIGS. 44 to 44, normalized by $\sigma_{c}$, against a variable representing $\beta^2$; FIG. 46 shows apparent dip angle $\theta_{app}(t)$ as a function of time based on calculated coaxial, coplanar, and cross-component transient responses from a $L=1$ m tool in a formation of $R_{c}=10$ $\Omega$m and $R_{c}/R_{c}=r_{0}$; FIG. 47 shows an electromagnetic induction tool in a formation layer comprising a package of alternating sets of sub-layers; FIG. 48 shows a graph of apparent resistivity in co-axial measurement and co-planar measurement of the geometry as in FIG. 47; FIG. 49 schematically shows directional components of an electromagnetic induction tool relative to an anisotropic anomaly; FIG. 50 shows a plot of the apparent conductivity ($\sigma_{app}(x, t)$) in both $z$ and $t$-coordinates for various distances $D$; FIG. 51 shows a plot of the apparent conductivity ($\sigma_{app}(x, t)$) in both $z$ and $t$-coordinates; FIG. 52 schematically shows a model of a structure involving a highly resistive layer (100 $\Omega$m) covered by a conductive local layer (1 $\Omega$m) which is covered by a resistive layer (10 $\Omega$m), whereby a coaxial tool is depicted in the resistive layer; FIG. 53A shows apparent resistivity in both $z$ and $t$ coordinates, whereby inflection points are joined using curve fitted lines; FIG. 53B shows an image log derived from FIG. 53A; FIG. 54A schematically shows a coaxial tool seen as approaching a highly resistive formation at a dip angle of approximately 30 degrees; FIG. 54B shows apparent dip response in both $t$ and $z$ coordinates for $z$-locations corresponding to those depicted in FIG. 54A.

**DETAILED DESCRIPTION OF THE INVENTION**

The present invention will now be described in relation to particular embodiments, which are intended in all respects to be illustrative rather than restrictive. Alternative embodiments will become apparent to those skilled in the art to which the present invention pertains without departing from its scope.

It will be understood that certain features and sub-combinations are of utility and may be employed without reference to other features and sub-combinations specifically set forth. This is contemplated and within the scope of the claims.

Embodiments of the invention relate to analysis of electromagnetic (EM) induction signals and to a system and method for determining distance and/or direction to an anomaly in a formation from a location within a wellbore. The analysis is sensitive to electromagnetic anomalies, in particular electromagnetic induction anomalies.

Both frequency domain excitation and time domain excitation have been used to excite electromagnetic fields for use in anomaly detection. In frequency domain excitation, a device transmits a continuous wave of a fixed or mixed frequency and measures responses at the same band of frequencies. In time domain excitation, a device transmits a square wave signal, triangular wave signal, pulsed signal or pseudo-random binary sequence as a source and measures the broadband earth response. Sudden changes in transmitter current cause transient signals to appear at a receiver caused by induction currents in the formation. The signals that appear at the receiver are called transient responses because the receiver signals start at a first value after a sudden change in transmitter current, and then they decay (or increase) with time to a new constant level at a second value. The technique disclosed herein implements the time domain excitation technique.

As set forth below, embodiments of the invention propose a general method to determine a direction from a measurement sub to a resistive or conductive anomaly using transient EM responses. As will be explained in detail, the direction to the anomaly is specified by a dip angle and an azimuth angle. Embodiments of the invention propose to define an apparent dip ($\theta_{app}(t)$) and an apparent azimuth ($\phi_{app}(t)$) by combinations of multi-axial, e.g. bi-axial or tri-axial, transient measurements. The true direction, in terms of dip and azimuth angles ($\{\theta, \phi\}$), may be determined from the analysis of the apparent direction ($\{\theta_{app}(t), \phi_{app}(t)\}$). For instance, the apparent direction ($\{\theta_{app}(t), \phi_{app}(t)\}$) approaches the true direction ($\{\theta, \phi\}$) as time $t$ increases, if the anomaly has a high thickness as seen from the tool.

Time-dependent values for apparent conductivity may be obtained from coaxial and coplanar electromagnetic induction measurements, and can respectively be denoted as $\sigma_{coaxial}(t)$ and $\sigma_{coplanar}(t)$. Both read the conductivity in the total present formation around the tool. The $\theta_{app}(t)$ and $\phi_{app}(t)$ both initially read zero when an apparent conductivity $\sigma_{coaxial}(t)$ and $\sigma_{coplanar}(t)$ from coaxial and coplanar...
measurements both read the conductivity of the formation surrounding the tool nearby. The apparent conductivity will be further explained below and can also be used to determine the location of an anomaly in a wellbore.

[0091] Whenever in the present specification the term “conductivity” is employed, it is intended to cover also its inverse equivalent “resistivity”, and vice versa. The same holds for the terms “apparent conductivity” and “apparent resistivity”.

[0092] FIGS. 1A and 1B illustrate systems that may be used to implement the embodiments of the method of the invention. A surface computing unit 10 may be connected with an electromagnetic measurement tool 2 disposed in a wellbore 4.

[0093] In FIG. 1A, the tool 2 is suspended on a cable 12. The cable 12 may be constructed of any known type of cable for transmitting electrical signals between the tool 2 and the surface computing unit 10.

[0094] In FIG. 1B, the tool is comprised in a measurement sub 11 and suspended in the wellbore 4 by a drill string 15. The drill string 15 further supports a drill bit 17, and may support a steering system 19. The steering system may be of a known type, including a rotatable steering system or a sliding steering system. The wellbore 4 traverses the earth formation 5 and it is an objective to precisely direct the drill bit 17 into a hydrocarbon fluid containing reservoir 6 to enable producing the hydrocarbon fluid via the wellbore. Such a reservoir 6 may manifest itself as an electromagnetic anomaly in the formation 5.

[0095] Referring again to both FIGS. 1A and 1B, one or more transmitters 16 and one or more receivers 18 may be provided for transmitting and receiving electromagnetic signals into and from the formation around the wellbore 4. A data acquisition unit 14 may be provided to transmit data to and from the transmitters 16 and receivers 18 to the surface computing unit 10.

[0096] Each transmitter 16 and/or receiver 18 may comprise a coil, wound around a support structure such as a mandrel. The support structure may comprise a non-conductive section to suppress generation of eddy currents. The non-conductive section may comprise one or more slots, optionally filled with a non-conductive material, or it may be formed out of a non-conductive material such as a composite plastic. Alternatively, the support structure is coated with a layer of a high-magnetic permeable material to form a magnetic shield between the antenna and the support structure.

[0097] Each transmitter 16 and each receiver 18 may be bi-axial or even tri-axial, and thereby contain components for sending and receiving signals along each of three axes. Accordingly, each transmitter module may contain at least one single or multi-axis antenna and may be a 3-orthogonal component transmitter. Each receiver may include at least one single or multi-axis electromagnetic receiving component and may be a 3-orthogonal component receiver.

[0098] A tool/borehole coordinate system is defined as having x, y, and z axes. The z-axis defines the direction from the transmitter T to the receiver R. It will be assumed hereinafter that the axial direction of the wellbore 4 coincides with the z-axis, whereby the x- and y-axes correspond to two orthogonal directions in a plane normal to the direction from the transmitter T to the receiver R and to the wellbore 4.

[0099] The data acquisition unit 14 may include a controller for controlling the operation of the tool 2. The data acquisition unit 14 preferably collects data from each transmitter 16 and receiver 18 and provides the data to the surface computing unit 10. The data acquisition unit 14 may comprise an amplifier and/or a digital to analogue converter, as described in co-pending U.S. application Ser. No. 11/689,980 filed on 22 Mar. 2007, incorporated herein by reference, to amplify the responses and/or convert to a digital representation of the responses before transmitting to the surface computing unit 10 via cable 12 and/or an optional telemetry unit 13.

[0100] The surface computing unit 10 may include computer components including a processing unit 30, an operator interface 32, and a tool interface 34. The surface computing unit 10 may also include a memory 40 including relevant coordinate system transformation data and assumptions 42, an optional direction calculation module 44, an optional apparent direction calculation module 46, and an optional distance calculation module 48. The optional direction and apparent direction calculation modules are described in more detail in already incorporated US patent application publication 2005/0092487 and need not be further described here, other than specifying that these optional modules may take into account formation anisotropy.

[0101] The surface computing unit 10 may include computer components including a processing unit 30, an operator interface 32, and a tool interface 34. The surface computing unit 10 may include a memory 40 including relevant coordinate system transformation data and assumptions 42, a direction calculation module 44, an apparent direction calculation module 46, and a distance calculation module 48. The surface computing unit 10 may further include a bus 50 that couples various system components including the system memory 40 to the processing unit 30. The computing system environment 10 is only one example of a suitable computing environment and is not intended to suggest any limitation as to the scope of use or functionality of the invention. Furthermore, although the computing system 10 is described as a computing unit located on a surface, it may optionally be located below the surface, incorporated in the tool, positioned at a remote location, or positioned at any other convenient location.

[0102] The memory 40 preferably stores one or more of modules 44, 46, and 48, which may be described as program modules containing computer-executable instructions, executable by the surface computing unit 10. Each module may comprise or make use of a computer readable medium that stores computer readable instructions for analyzing one or more detected time-dependent transient electromagnetic response signals that have been detected by a tool suspended inside a wellbore traversing a subterranean formation after inducing one or more electromagnetic fields in the formation. The instructions may implement any part of the disclosure that follows herein below.

[0103] For example, the program module 44 may contain computer executable instructions to calculate a direction to an anomaly within a wellbore. The program module 48 may contain computer executable instructions to calculate a distance to an anomaly or a thickness of the anomaly. The stored data 42 may include data pertaining to the tool coordinate system and the anomaly coordinate system and other data for use by the program modules 44, 46, and 48. Preferably, the computer readable instructions take into
account electromagnetic anisotropy of at least one formation layer in the subterranean formation. For further details on the computing system 10, including storage media and input/output devices, reference is made to US patent application publication 2005/0092487, incorporated herein by reference. Accordingly, additional details concerning the internal construction of the computer 10 need not be disclosed in connection with the present invention.

[0104] FIG. 2 is a flow chart illustrating the procedures involved in performing the invention. Generally, in procedure A, the transmitters 16 transmit electromagnetic signals. In procedure B, the receivers 18 receive transient responses. In procedure C, the system processes the transient responses. The procedures may then end or start again.

[0105] Procedure C may comprise determining a distance and/or a direction to the anomaly may be determined. Procedure C may comprise creating an image of formation features based on the transient electromagnetic responses. Electromagnetic anisotropy of at least one of the formation layers may be taken into account.

[0106] FIGS. 3-6 illustrate the technique for implementing procedure C for determining distance and/or direction to the anomaly. FIGS. 6 and 41 to 49 illustrate how electromagnetic anisotropy may be taken into account, e.g., in determining distance and/or direction to the anomaly.

Tri-Axial Transient EM Responses

[0107] FIG. 3 illustrates directional angles between tool coordinates and anomaly coordinates. A transmitter coil T is located at an origin that serves as the origin for each coordinate system. A receiver R is placed at a distance L from the transmitter. An earth coordinate system, includes a Z-axis in a vertical direction, an X-axis and a Y-axis in the East and the North directions, respectively. The deviated borehole is specified in the earth coordinates by a deviation angle θ, and its azimuth angle θ. A resistivity anomaly A is located at a distance D from the transmitter in the direction specified by a dip angle (θ) and its azimuth (φ).

[0108] In order to practice embodiments of the method, FIG. 4A shows the definition of the tool/borehole coordinate system having x, y, and z axes. The z-axis defines the direction from the transmitter T to the receiver R. The tool coordinates in FIG. 4A are specified by rotating the earth coordinates (X, Y, Z) in FIG. 3 by the azimuth angle (θ) around the Z-axis and then rotating by θ around the Y-axis to arrive at the tool coordinates (x, y, z). The direction of the anomaly is specified by the dip angle (v) and the azimuth angle (φ) where:

\[
\cos \theta = \frac{b_{1} - b_{2}}{c_{1}} = \cos \theta_{x} \cos \theta_{y} + \sin \theta_{x} \sin \theta_{y} \cos (\phi - \phi_{a})
\]

\[
\tan \phi = \frac{\sin \theta_{x} \sin \theta_{y} \cos (\phi - \phi_{a})}{\cos \theta_{x} \sin \theta_{y} \cos (\phi - \phi_{a}) - \sin \theta_{x} \cos \theta_{y}}
\]

Similarly, FIG. 4B shows the definition of an anomaly coordinate system having a, b, and c axes. The c-axis defines the direction from the transmitter T to the center of the anomaly A. The anomaly coordinates in FIG. 4B are specified by rotating the earth coordinates (X, Y, Z) in FIG. 3 by the azimuth angle (φ) around the Z-axis and subsequently rotating by θ around the b-axis to arrive at the anomaly coordinates (a, b, c). In this coordinate system, the direction of the borehole is specified in a reverse order by the azimuth angle (φ) and the dip angle (v).

Transient Responses in Two Coordinate Systems

[0110] The method is additionally based on the relationship between the transient responses in two coordinate systems. The magnetic field transient responses at the receivers [R, R, R] which are oriented in the [x, y, z] axis direction of the tool coordinates, respectively, are noted as

\[
\begin{bmatrix}
V_{x}\, V_{y}\, V_{z}
\end{bmatrix} = \begin{bmatrix}
R_{x}\, R_{y}\, R_{z}
\end{bmatrix}
\]

wherein the right-hand side of the equation represents all combinations of receiver axis and transmitter axis, whereby \(V_{j} = R_{j}\) denotes voltage response sensed by receiver \(R_{j}\) (i=x, y, z) from signal transmitted by transmitter \(T_{j}\) (j=x, y, z). Each transmitter may comprise a magnetic dipole source, \([M_{x}, M_{y}, M_{z}]\), in any direction.

[0111] When the resistivity anomaly is distant from the tool, the formation near the tool is seen as a homogeneous formation. For simplicity, the method may assume that the formation is isotropic. Only three non-zero transient responses exist in a homogeneous isotropic formation. These include the coaxial response and two coplanar responses. Coaxial response \(V_{x}(t)\) is the response when both the transmitter and the receiver are oriented in the common tool axis direction. Coplanar responses, \(V_{y}(t)\) and \(V_{y}(t)\), are the responses when both the transmitter T and the receiver R are aligned parallel to each other but their orientation is perpendicular to the tool axis. All of the cross-component responses are identically zero in a homogeneous isotropic formation. Cross-component responses are either from a longitudinally oriented receiver with a transverse transmitter, or vice versa. Another cross-component response is also zero between a mutually orthogonal transverse receiver and transverse transmitter.

[0112] The effect of the resistivity anomaly is seen in the transient responses as time increases. In addition to the coaxial and the coplanar responses, the cross-component responses \(V_{y}(t)\) (i=x, j=x, y, z) become non-zero.

[0113] The magnetic field transient responses may also be examined in the anomaly coordinate system. The magnetic field transient responses at the receivers [R, R, R] that are oriented in the [a, b, c] axis direction of the anomaly coordinates, respectively, may be noted as

\[
\begin{bmatrix}
V_{a}\, V_{b}\, V_{c}
\end{bmatrix} = \begin{bmatrix}
R_{a}\, R_{b}\, R_{c}
\end{bmatrix}
\]

wherein the right-hand side of the equation represents all combinations of receiver orientation and transmitter orientation, whereby \(V_{j} = R_{j}\) denotes voltage response sensed by receiver \(R_{j}\) (in orientation i=x, b, c) from signal transmitted by transmitter \(T_{j}\) (in orientation j=x, b, c). Each transmitter may comprise a magnetic dipole source, \([M_{x}, M_{y}, M_{z}]\), along the orientation a, b, or c.
When the anomaly is large and distant compared to the transmitter-receiver spacing, the effect of spacing can be ignored and the transient responses can be approximated with those of the receivers near the transmitter. Then, the method assumes that axial symmetry exists with respect to the c-axis that is the direction from the transmitter to the center of the anomaly. In such an axially symmetric configuration, the cross-component responses in the anomaly coordinates are identically zero in time-domain measurements.

\[
\begin{bmatrix}
V_{ax} & V_{ay} & V_{az} \\
V_{ax} & V_{ay} & V_{az} \\
V_{ax} & V_{ay} & V_{az}
\end{bmatrix} \approx \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

(5)

The magnetic field transient responses in the tool coordinates are related to those in the anomaly coordinates by a simple coordinate transformation \( P(v, \phi) \) specified by the dip angle (\( v \)) and azimuth angle (\( \phi \)).

\[
P(v, \phi) = \begin{bmatrix}
\cos(\phi) \cos(\phi) \\
\sin(\phi) \cos(\phi) \\
\sin(\phi) \sin(\phi)
\end{bmatrix}
\]

(7)

Determination of Direction

The assumptions set forth above contribute to determination of target direction, which is defined as the direction of the anomaly from the origin. The tool is in the origin. When axial symmetry in the anomaly coordinates is assumed, the transient response measurements in the tool coordinates are constrained and the two directional angles may be determined by combinations of tri-axial responses.

\[
\begin{bmatrix}
V_{ax} & V_{ay} & V_{az} \\
V_{ax} & V_{ay} & V_{az} \\
V_{ax} & V_{ay} & V_{az}
\end{bmatrix} = P(\phi, \theta) \begin{bmatrix}
V_{ax} & V_{ay} & V_{az} \\
V_{ax} & V_{ay} & V_{az} \\
V_{ax} & V_{ay} & V_{az}
\end{bmatrix} P(\phi, \theta)
\]

(6)

In terms of each tri-axial response

\[
V_{xx} = (V_{ax} \cos^2(\phi) + V_{ay} \sin^2(\phi)) \cos(\phi) + V_{az} \sin^2(\phi)
\]

(9)

The following relations can be noted:

\[
\begin{align*}
V_{xx} &= V_{ax} + V_{ay} + V_{az} \\
V_{yy} &= V_{ay} + V_{az} \\
V_{yz} &= V_{az} \\
V_{zx} &= V_{ax} + V_{ay} + V_{az} \\
V_{xz} &= V_{ax} + V_{az} \\
V_{zy} &= V_{ay} + V_{az}
\end{align*}
\]

(11)

Several distinct cases can be noted. In the first of these cases, when none of the cross-components is zero, \( V_{xx} \neq 0 \) nor \( V_{yy} \neq 0 \) nor \( V_{zz} \neq 0 \), then the azimuth angle \( \phi \) is not zero nor \( \pi/2 \) (90°), and can be determined by,

\[
\phi = \frac{1}{2} \tan^{-1} \frac{V_{ax} + V_{ay}}{V_{ax} - V_{ay}}
\]

(12)

By noting the relation,

\[
\frac{V_{y}}{V_{z}} = \tan(\phi) \cos(\phi) \quad \text{and} \quad \frac{V_{x}}{V_{z}} = \tan(\phi) \sin(\phi)
\]

(13)

the dip (deviation) angle \( v \) is determined by,

\[
\tan(v) = \sqrt{\left(\frac{V_{x}}{V_{z}}\right)^2 + \left(\frac{V_{y}}{V_{z}}\right)^2}
\]

(14)

In the second case, when \( V_{xx} = 0 \) and \( V_{yy} = 0 \), then \( v = 0 \) or \( \phi = 0 \) or \( \pi (180°) \) or \( \phi = \pi/2 \) (90°) and \( v = \pi/2 \) (90°), as the coaxial and the coplanar responses should differ from each other on \( V_{ax} \neq V_{az} \).

If \( \phi = 0 \), then the dip angle \( v \) is determined by,

\[
\theta = \frac{1}{2} \tan^{-1} \frac{V_{yy} + V_{yz}}{V_{yy} - V_{yz}}
\]

(15)

If \( \phi = \pi \) (180°), then the dip angle \( v \) is determined by,

\[
\theta = \frac{1}{2} \tan^{-1} \frac{V_{xx} + V_{yx}}{V_{xx} - V_{yx}}
\]

(16)

Also, with regard to the second case, If \( v = 0 \), then \( V_{xx} = V_{yy} \) and \( V_{yy} = 0 \). If \( \phi = \pi/2 \) (90°) and \( v = \pi/2 \) (90°), then \( \phi = V_{ax} \) and \( V_{aa} = 0 \). These instances are further discussed below with relation to the fifth case.

In the third case, when \( V_{xy} = 0 \) and \( V_{yx} = 0 \), then \( \phi = \pi/2 \) (90°) or \( v = 0 \) or \( \phi = 0 \) or \( \phi = -\pi/2 \) (90°).
If \( \phi = \pi/2 \), then the dip angle \( \nu \) is determined by,

\[
\nu = -\frac{1}{2} \tan^{-1} \frac{V_{xy} + V_y}{V_{xy} - V_y}
\]

(17)

If \( \phi = -\pi/2 \), then the dip angle \( \nu \) is determined by,

\[
\nu = \frac{1}{2} \tan^{-1} \frac{V_{xy} + V_y}{V_{xy} - V_y}
\]

(18)

Also with regard to the third case, if \( \nu = 0 \), then \( V_{xy} = V_{xy} \) and \( V_y = 0 \). If \( \phi = 0 \) and \( \nu = \pm \pi/2 \) (90°), \( V_{xy} = V_{xy} \) and \( V_y = 0 \). These situations are further discussed below with relation to the fifth case.

The azimuth angle \( \phi \) is determined from the tri-axial responses if the tool rotation angle \( \psi \) is known. To the contrary, the dip (deviation) angle \( \nu \) is determined by,

\[
\tan \nu = \sqrt{\left( \frac{V_{xy}}{V_y} \right)^2 + \left( \frac{V_{yz}}{V_z} \right)^2}
\]

(26)

without knowing the tool orientation \( \psi \).

Apparent Dip Angle and Azimuth Angle and the Distance to the Anomaly

The dip and the azimuth angle described above indicate the direction of a resistivity anomaly determined by a combination of tri-axial transient responses at a time \( t \) when the angles have deviated from a zero value. When \( t \) is small or close to zero, the effect of such anomaly is not apparent in the transient responses as all the cross-component responses are vanishing. To identify the anomaly and estimate not only its direction but also the distance, it is useful to define the apparent azimuth angle \( \phi_{app}(t) \) and the apparent dip angle \( \nu_{app}(t) \) by:

\[
\phi_{app}(t) = \frac{1}{2} \tan^{-1} \frac{V_{xy}(t) + V_y(t)}{V_{xy}(t) - V_y(t)}
\]

(27)

and the effective dip angle \( \nu_{app}(t) \) by

\[
\nu_{app}(t) = \tan^{-1} \frac{V_{xy}(t)}{V_y(t)} = \tan^{-1} \frac{V_{xy}(t)}{V_{xy}(t)}
\]

(28)

for the time interval when \( \phi_{app}(t) \neq 0 \) nor \( \pi/2 \) (90°). For simplicity, the case examined below is one in which none of the cross-component measurements is identically zero: \( V_{xy} \neq 0 \), \( V_{xy} \neq 0 \), and \( V_{xy} \neq 0 \).
For the time interval when \( \phi_{app}(t) = 0 \), \( v_{app}(t) \) is defined by,

\[
\theta_{app}(t) = -\frac{1}{2} \tan^{-1} \frac{V_x(t) + V_y(t)}{V_x(t) - V_y(t)}
\]  

(29)

For the time interval when \( \phi_{app}(t) = \pi/2 \) (90°), \( v_{app}(t) \) is defined by,

\[
\theta_{app}(t) = -\frac{1}{2} \tan^{-1} \frac{V_x(t) + V_y(t)}{V_x(t) - V_y(t)}
\]  

(30)

When \( t \) is small and the transient responses do not see the effect of a resistivity anomaly at distance, the effective angles are identically zero, \( \phi_{app}(t) = \theta_{app}(t) = 0 \). As \( t \) increases, when the transient responses see the effect of the anomaly, \( \phi_{app}(t) \) and \( \theta_{app}(t) \) begin to show the true azimuth and the true dip angles. The distance to the anomaly may be indicated at the time when \( \phi_{app}(t) \) and \( \theta_{app}(t) \) start deviating from the initial zero values. As shown below in a modeling example, the presence of an anomaly is detected much earlier in time in the effective angles than in the apparent conductivity \( (\sigma_{app}(t)) \). Even if the resistivity of the anomaly may not be known until \( \sigma_{app}(t) \) is affected by the anomaly, its presence and the direction can be measured by the apparent angles. With limitation in time measurement, the distant anomaly may not be seen in the change of \( \sigma_{app}(t) \) but is visible in \( \phi_{app}(t) \) and \( \theta_{app}(t) \).

**FIRST MODELING EXAMPLE**

FIG. 6 depicts a simplified modeling example wherein a resistivity anomaly \( A \) is depicted in the form of, for example, a massive salt dome in a formation 5. The salt interface 55 may be regarded as a plane interface. FIG. 6 also indicates coaxial 60, coplanar 62, and cross-component (64) measurement arrangements, wherein a transmitter coil and a receiver coil are spaced a distance \( L \) apart from each other. It will be understood that in a practical application, separate tools may be employed for each of these arrangements, or a multiple orthogonal tool. For further simplification, it can be assumed that the azimuth direction of the salt face as seen from the tool is known. Accordingly, the remaining unknowns are the first distance \( D_x \) to the salt face 55 from the tool, the second distance \( D_y \) of the other side of the salt from the tool, the isotropic or anisotropic formation resistivity, and the approach angle (or dip angle) \( \theta \) as shown in FIG. 6. The thickness \( A \) of the salt dome is defined as \( \Delta = D_x - D_y \). In this case the resistivity in the anomaly \( A \) is anisotropic, the electromagnetic properties of the anomaly may be characterized by normal resistivity \( R_{n} \) in the direction of the principal axis of the anisotropy and in-plane resistivity \( R_{pp} \) or in-plane conductivity \( \sigma_{pp} \) in any direction within a plane perpendicular to the principal axis. In case of anisotropy, \( R_{n,pp} = \frac{1}{\sigma_{pp}} \).

Before discussing anisotropy in more detail, isotropic formations will first be illustrated with resistivity \( R_{n} = R_{pp} = R_{l} \) (or its inverse \( \sigma_{n} = \sigma_{pp} = \sigma_{l} \)).

FIG. 7 and FIG. 8 show the calculated transient voltage response \( V(t) \) from coaxial \( V_{cc}(t) \) (line 65), coplanar \( V_{cc}(t) \) (line 66), and cross-component \( V_{cc}(t) \) (line 67) measurements for a tool having \( L = 1 \) m, for \( \theta = 30^\circ \), and located at a distance of \( D_x = 10 \) m respectively \( D_y = 100 \) m away from a salt face 55. In the calculations, \( D_x \) has been assumed much larger than 100 m, such that within the timescale of the calculation (up to 1 sec) any influence from the other side of the salt A is not detectible in the transient response. Moreover, when the anomaly is large and distant compared to the transmitter-receiver spacing 1, the effect of the spacing 1 can be ignored and the transient responses can be approximated with those of the receivers near the transmitter.

The apparent dip angle \( \theta_{app}(t) \), as calculated by

\[
\theta_{app}(t) = -\frac{1}{2} \tan^{-1} \frac{V_x(t) + V_y(t)}{V_x(t) - V_y(t)}
\]  

(31)

is shown in FIG. 9 for a L=1 m tool assembly when the salt face 55 is \( D_x=10 \) m away and at the approach angle of \( \theta = 30^\circ \).

The apparent conductivity \( (\sigma_{app}(t)) \) from both the coaxial \( (V_{cc}(t)) \) of FIG. 7 and the coplanar \( (V_{cc}(t)) \) of FIG. 7 responses are shown in FIG. 10 (lines 68, respectively line 69), wherein the approach angle (\( \theta = 30^\circ \)) and salt face distance \( (D_x=10 \) m) are the same as in FIG. 9. Details of how the apparent conductivities are calculated will be provided below.

Note that the true direction from the tool to the salt face (i.e., 30°) is reflected in the apparent dip \( \theta_{app}(t) \) plot of FIG. 9 as early as \( 10^{-4} \) second, when the presence of the resistivity anomaly is barely detected in the apparent conductivity \( (\sigma_{app}(t)) \) plot of FIG. 10. It takes almost \( 10^{-3} \) second for the apparent conductivity to approach an asymptotic \( \sigma_{app}(\text{late} \ t) \) value.

FIG. 11 shows the apparent dip \( \theta_{app}(t) \) for the L=1 m tool assembly when the salt face is \( D_x = 10 \) m away, but at different angles between the tool axis and the target varying from 0° to 90° in 15° increments. The approach angle \( \theta \) may be reflected at any angle in about \( 10^{-4} \) sec.

FIG. 11 and FIGS. 12 and 13 compare the apparent dip \( \theta_{app}(t) \) for different salt face distances \( (D_x=10 \) m; 50 m; and \( 100 \) m) and different angles between the tool axis and the target.

The distance to the salt face can be also determined by the transition time at which \( \theta_{app}(t) \) takes an asymptotic value. Even if the salt face distance \( (D_x) \) is 100 m, it can be identified and its direction can be measured by the apparent dip \( \theta_{app}(t) \).

In summary, the method considers the coordinate transformation of transient EM responses between tool-fixed coordinates and anomaly-fixed coordinates. When the anomaly is large and far away compared to the transmitter-
receiver spacing, one may ignore the effect of spacing and approximate the transient EM responses with those of the receivers near the transmitter. Then, one may assume axial symmetry exists with respect to the z-axis that defines the direction from the transmitter to the anomaly. In such an axially symmetric configuration, the cross-component responses in the anomaly-fixed coordinates are identically zero. With this assumption, a general method is provided for determining the direction to the resistivity anomaly using tri-axial transient EM responses.

The method defines the apparent dip $\theta_{app}(t)$ and the apparent azimuth $\phi_{app}(t)$ by combinations of tri-axial transient measurements. The apparent direction $\{\theta_{app}(t), \phi_{app}(t)\}$ reads the true direction $\{\theta, \phi\}$ at later time. The $\theta_{app}(t)$ and $\phi_{app}(t)$ both read zero when $t$ is small and the effect of the anomaly is not sensed in the transient responses or the apparent conductivity. The conductivities $\sigma_{max}(t)$ and $\sigma_{planar}(t)$ from the coaxial and coplanar measurements both indicate the conductivity of the near formation around the tool.

Deviations of the apparent direction $\{\theta_{app}(t), \phi_{app}(t)\}$ from zero identify the anomaly. The distance to the anomaly is measured by the time when the apparent direction $\{\theta_{app}(t), \phi_{app}(t)\}$ starts to deviate from zero or by the time when the apparent direction $\{\theta_{app}(t), \phi_{app}(t)\}$ starts approaches the true direction $\{\theta, \phi\}$. The distance can be also measured from the change in the apparent conductivity. However, the anomaly is identified and measured much earlier in time in the apparent direction than in the apparent conductivity.

**Apparent Conductivity**

As set forth above, apparent conductivity can be used as an alternative technique to apparent angles in order to determine the location of an anomaly in a wellbore. The time-dependent apparent conductivity can be defined at each point of a time series at each logging depth. The apparent conductivity at a logging depth $z$ is defined as the conductivity of a homogeneous formation that would generate the same tool response measured at the selected position.

In transient EM logging, transient data are collected at a logging depth or tool location $z$ as a time series of induced voltages in a receiver loop. Accordingly, time dependent apparent conductivity ($\sigma(t; z)$) may be defined at each point of the time series at each logging depth, for a proper range of time intervals depending on the formation conductivity and the tool specifications.

The induced voltage of a coaxial tool with transmitter-receiver spacing $L$ in the homogeneous formation of conductivity $\sigma$ is given by,

$$ V_{app}(t) = C \frac{(\mu_0 \sigma_{app}(t))^{1/2}}{8 \pi z^2} \epsilon^{-z^2} = \frac{\mu_0 \sigma_{app}(t)}{4 \pi} \frac{L^2}{t} $$

and $C$ is a constant.

The time-changing apparent conductivity depends on the voltage response in a coaxial tool $V_{app}(t)$ at each time of measurement as:

$$ C \frac{(\mu_0 \sigma_{app}(t))^{1/2}}{8 \pi z^2} \epsilon^{-z^2} = V_{app}(t) \text{ where } \sigma_{app}(t) = \frac{\mu_0 \sigma_{app}(t)}{4 \pi} \frac{L^2}{t} $$

and $V_{app}(t)$ on the right hand side is the measured voltage response of the coaxial tool. From a single type of measurement (coaxial, single spacing), the greater the spacing $L$, the larger the measurement time $(t)$ should be to apply the apparent conductivity concept. The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t) = \sigma$. The deviation from a constant $(c)$ at time $(t)$ suggests a conductivity anomaly in the region specified by time $(t)$.

The induced voltage of the coplanar tool with transmitter-receiver spacing $L$ in the homogeneous formation of conductivity $\sigma$ is given by,

$$ V_{app}(t) = C \frac{(\mu_0 \sigma_{app}(t))^{1/2}}{8 \pi z^2} \epsilon^{-z^2} \sigma(t) \text{ where } \sigma(t) = \frac{\mu_0 \sigma_{app}(t)}{4 \pi} \frac{L^2}{t} $$

and $C$ is a constant. At small values of $t$, the coplanar voltage changes polarity depending on the spacing $L$ and the formation conductivity.

Similarly to the coaxial tool response, the time-changing apparent conductivity is defined from the coplanar tool response $V_{app}(t)$ at each time of measurement as,

$$ C \frac{(\mu_0 \sigma_{app}(t))^{1/2}}{8 \pi z^2} \epsilon^{-z^2} \sigma_{app}(t) = V_{app}(t) \text{ where } \sigma_{app}(t) = \frac{\mu_0 \sigma_{app}(t)}{4 \pi} \frac{L^2}{t} $$

and $V_{app}(t)$ on the right hand side is the measured voltage response of the coplanar tool. The longer the spacing, the larger the value $t$ should be to apply the apparent conductivity concept from a single type of measurement (coplanar, single spacing). The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t) = \sigma$.

When there are two coaxial receivers, the ratio between the pair of voltage measurements is given by,

$$ \frac{V_{app}(L_1; t)}{V_{app}(L_2; t)} = e^{-\frac{\mu_0 \sigma_{app}(t)}{4 \pi} \frac{L_1^2}{t}} $$

where $L_1$ and $L_2$ are transmitter-receiver spacing of two coaxial tools.
at each time of measurement. The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t)=\sigma$.

The apparent conductivity is similarly defined for a pair of coplanar tools or for a pair of coaxial and coplanar tools. The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t)=\sigma$. The deviation from a constant ($\sigma$) at time ($t$) suggests a conductivity anomaly in the region specified by time ($t$).

As will be explained below, apparent conductivity ($\sigma_{app}(t)$), whether coaxial or coplanar, may reveal three parameters in relation to a two-layer formation, including:
1. the conductivity of a local first layer in which the tool is located;
2. the conductivity of one or more adjacent layers or beds; and
3. the distance of the tool to the layer boundaries.

Analysis of Coaxial Transient Response in Two-Layer Models

To illustrate usefulness of the concept of apparent conductivity, the transient response of a tool in a two-layer earth model, as in FIG. 14 for example, can be examined.

FIG. 14 illustrates a coaxial tool 80 in which both a transmitter coil (T) and a receiver coil (R) are wound around the common tool axis z and spaced a distance L apart. The symbols $\sigma_1$ and $\sigma_2$ may represent the conductivities of two formation layers. The coaxial tool 80 is placed in a horizontal well 88 traversing formation layer 5 and extending parallel to the layer interface 55. In the present example, a horizontal well is depicted such that the distance from the tool to the layer boundary corresponds to the distance of the horizontal borehole to the layer boundary. Under a more general circumstance, the relative direction of a borehole and tool to the bed interface is not known.

The calculated transient voltage response V(t) for the L=1 m transmitter-receiver offset coaxial tool at various distances D between the tool 80 and the layer boundary 55 is shown in FIG. 15 for D=1, 5, 10, 25, and 50 m. The formation can be analyzed using these responses, employing apparent conductivity as further explained with regard to FIGS. 16 and 17.

FIG. 16 shows the voltage data of FIG. 15 plotted in terms of apparent conductivity, for a geometry wherein $\sigma_1$=0.1 S/m (R$_1$=10 $\Omega$m) and $\sigma_2$=1 S/m (R$_2$=1 $\Omega$m). Similarly, FIG. 17 illustrates the apparent conductivity in a two-layer model where $\sigma_1$=1 S/m (R$_1$=1 $\Omega$m) and $\sigma_2$=0.1 S/m (R$_2$=10 $\Omega$m).

The apparent conductivity plots reveal a “constant” conductivity at small t, and at large t but having a different value, and a transition time $t_\tau$ that marks the transition between the two “constant” conductivity values and depends on the distance D.

As will be further explained below, in a two-layer resistivity profile, the apparent conductivity as t approaches zero can identify the layer conductivity $\sigma_1$ around the tool, while the apparent conductivity as t approaches infinity can be used to determine the conductivity $\sigma_2$ of the adjacent layer at a distance. The distance to the bed boundary 55 from the tool 80 can also be measured from the transition time $t_\tau$, observed in the apparent conductivity plots.

At small values of $t$, the tool reads the apparent conductivity $\sigma_1$ of the first layer 5 around the tool 80. Conductivity at small values of t is thought to correspond to the conductivity of the local layer 5 where the tool is located in. At small values of t, the signal reaches directly from the transmitter without interfering with the bed boundary. Namely, the signal is affected only by the conductivity $\sigma_1$ around the tool.

At large values of t, the tool reads 0.4 S/m for a two-layer model where either $\sigma_1$=1 S/m (R$_1$=1 $\Omega$m) and $\sigma_2$=0.1 S/m (R$_2$=10 $\Omega$m), or $\sigma_1$=0.1 S/m (R$_1$=10 $\Omega$m) and $\sigma_2$=1 S/m (R$_2$=1 $\Omega$m). The value of 0.4 is believed to correspond to some average between the conductivities of the two layers, because at large values of t, nearly half of the signals come from the formation below the tool and the remaining signals come from above, if the time for the signal to travel the distance between the tool and the bed boundary is small.

This is further investigated in FIG. 18, which shows examples of the $\sigma_{app}(t)$ plots for D=1 m and L=1 m, but for different resistivity ratios of the target layer 2 while the local conductivity ($\sigma_1$) is fixed at 1 S/m (R$_1$=1 $\Omega$m). The apparent conductivity at large values of t is determined by the target layer 2 conductivity, as shown in line 71 in FIG. 19 when $\sigma_1$ is fixed at 1 S/m.

Numerically, the late time conductivity may be approximated by the square root average of two-layer conductivities as:

$$\sqrt{\sigma_{app}(\infty; \sigma_1, \sigma_2)} = \sqrt{\sqrt{\sigma_1^2} + \sqrt{\sigma_2^2}}.$$  (39)

This is depicted as line 72 in FIG. 19.

Thus, the conductivity at large values of t (as t approaches infinity) can be used to estimate the conductivity ($\sigma_2$) of the adjacent layer when the local conductivity ($\sigma_1$) near the tool is known, for instance from the conductivity as t approaches zero as illustrated in FIG. 20.

Estimation of D, The Distance to the Electromagnetic Anomaly

The distance D from the tool to the bed is reflected in the transition time $t_\tau$. The transition time at which the apparent conductivity $\sigma_{app}(t)$ starts deviating from the local conductivity $\sigma_1$ towards the conductivity at large values of t depends on D and L, as shown in FIG. 21.

For convenience, the transition time $t_\tau$ can be defined as the time at which the $\sigma_{app}(t)$ takes a cutoff conductivity ($\sigma_c$). In this case, the cutoff conductivity is represented by the arithmetic average between the conductivity as t approaches zero and the conductivity as t approaches infinity. The transition time $t_\tau$ is dictated by the ray path RP:

$$RP = \sqrt{\left(\frac{L}{2}\right)^2 + D^2},$$  (40)

that is the shortest distance for the electromagnetic signal traveling from the transmitter to the bed boundary, to the receiver, independently of the resistivity of the two layers.
Conversely, the distance (D) to the anomaly can be estimated from the transition time (t), as shown in FIG. 22.

Look-Ahead Capabilities of EM Transient Method

By analyzing apparent conductivity or its inherent inverse equivalent (apparent resistivity), the present invention can identify the location of a resistivity anomaly (e.g., a conductive anomaly and a resistive anomaly). Further, resistivity or conductivity can be determined from the coaxial and/or coplanar transient responses. As explained above, the direction to the anomaly can be determined if the cross-component data are also available. To further illustrate the usefulness of these concepts, the foregoing analysis may also be used to detect an anomaly at a distance ahead of the drill bit.

FIG. 23 shows a coaxial tool 80 with transmitter-receiver spacing L placed in, for example, a vertical well 88 approaching or just beyond an adjacent bed that is a resistivity anomaly. The tool 80 includes both a transmitter coil T and a receiver coil R, which are wound around a common tool axis and are oriented in the tool axis direction. The symbols σ1 and σ2 may represent the conductivities of two formation layers, and D the distance between the tool 80 (e.g., the transition antenna T) and the layer boundary 55.

The calculated transient voltage response of the L=1 m (transmitter-receiver offset) coaxial tool at different distances (D=1, 5, 10, 25, and 50 m) as a function of t is shown in FIG. 24, in a case wherein σ1=0.1 S/m (corresponding to R1=10 Ωm), and σ2=1 S/m (corresponding to R2=1 Ωm). Though difference is observed among responses at different distances, it is not straightforward to identify the resistivity anomaly directly from these responses.

The same voltage data of FIG. 24 is plotted in terms of the apparent conductivity (σ_app(t)) in FIG. 25. From this Figure, it is clear that the coaxial response can identify an adjacent bed of higher conductivity at a distance. Even a L=1 m tool can detect the bed at 10, 25, and 50 m away, if low voltage response can be measured for 0.1-1 seconds long.

The σ_app(t) plot exhibits at least three parameters very distinctly in the figure: the early time conductivity; the late time conductivity; and the transition time that moves as the distance (D) changes. In FIG. 25, it should be noted that, at early time whereby t is close to zero, the tool reads the apparent conductivity of 0.1 S/m, which is representative of the layer just around the tool. The signal that reaches the receiver R not yet contains information about the boundary 55. At later time, the tool reads close to 0.55 S/m, representing an arithmetic average between the conductivities of the two layers. At later time, t→∞, nearly half of the signals come from the formation below the tool and the other half from above the tool, if the time to travel the distance (D) of the tool to the bed boundary is small. The distance D is reflected in the transition time t.

FIG. 26 illustrates the σ_app(t) plot of the coaxial transient response in the two-layer model of FIG. 23 for an L=1 m tool at different distances (D), except that the conductivity of the local layer (σ1) is 1 S/m (R1=1 Ωm) and the conductivity of the target layer (σ2) is 0.1 S/m (R2=10 Ωm). Again, the tool reads at early time the apparent conductivity of 1.0 S/m that is of the layer just around the tool. At later time, the tool reads about 0.55 S/m, the same average conductivity value as in FIG. 25. The distance (D) is reflected in the transition time t.

Hence, the transient electromagnetic response method can be used as a look-ahead resistivity logging method.

FIG. 27 compares the σ_app(t) plot of FIG. 25 and FIG. 26 for L=1 m and D=50 m. The late time conductivity is determined solely by the conductivities of the two layers (σ1 and σ2) alone. It is not affected by where the tool is located in the two layers. However, because of the deep depth of investigation, the late time conductivity is not readily reached even at t=1 second, as shown in FIG. 25. In practice, the late time conductivity may have to be approximated by σ_app(t→∞) which slightly depends on D as illustrated in FIG. 25.

Numerically, the late time apparent conductivity may be approximated by the arithmetic average of two-layer conductivities as:

σ_app(t→∞) ≈ 0.5(σ1 + σ2).

This is reasonable considering that, with the coaxial tool, the axial transmitter induces the eddy current parallel to the bed boundary. At later time, the axial receiver receives horizontal current nearly equally from both layers. As a result, the late time conductivity must see conductivity of both formations with nearly equal weight.

FIG. 28 compares the σ_app(t) plots for D=50 m but with different spacing L. The σ_app(t) reaches a nearly constant late time apparent conductivity at later times as L increases. The late time apparent conductivity (σ_app(t→∞)) is nearly independent of L. However, the late time conductivity defined at t=1 second, depends on slightly the distance (D).

Thus, the late time apparent conductivity (σ_app(t→∞)) at t=1 second can be used to estimate the conductivity of the adjacent layer (σ2) when the local conductivity near the tool (σ1) is known, for instance, from the early time apparent conductivity (σ_app(t=0)=σ1).

Estimation of the Distance (D) to the Electromagnetic Anomaly

The transition time (t<sub>L</sub>) at which the apparent conductivity starts deviating from the local conductivity (σ<sub>L</sub>) toward the late time conductivity clearly depends on D, the distance of the tool to the bed boundary, as shown in FIG. 25 for a L=1 m tool.

For convenience, the transition time (t<sub>L</sub>) is defined by the time at which the σ_app(t) takes the cutoff conductivity (σ<sub>B</sub>), that is, in this example, the arithmetic average between the early time and the late time conductivities:

σ<sub>B</sub> = (σ_app(t=0)+σ_app(t→∞))/2.

The transition time (t<sub>L</sub>) is dictated by the ray-path RP, D minus 1/2 that is, half the distance for the EM signal to travel from the transmitter to the bed boundary to the receiver, independently on the resistivity of the two layers. Conversely, the distance (D) can be estimated from the transition time (t<sub>L</sub>) as shown in FIG. 29 when L=1 m.

Analysis of Coplanar Transient Responses in Two-Layer Models

While the coaxial transient data were examined above, the coplanar transient data are equally useful as a look-ahead resistivity logging method.
Fig. 30 shows a coplanar tool 80 with transmitter-receiver spacing L placed in a well 88 and approaching (or just beyond) layer boundary 85 of an adjacent bed that is the resistivity anomaly. On the coplanar tool, both a transmitter T and a receiver R are oriented perpendicularly to the tool axis z and parallel to each other. The symbols \( \sigma_1 \) and \( \sigma_2 \) may represent the conductivities of two formation layers.

Corresponding to Fig. 25 for coaxial tool responses where \( L = 1 \) m, the apparent conductivity \( \sigma_{app}(t) \) for calculated coplanar responses is plotted in Fig. 31 for different tool distances from the bed boundary 85. It is clear that the coplanar response can also identify an adjacent bed of higher conductivity at a distance. Even a L=1 m tool can detect the bed at 10 m, 25 m, and 50 m away if low voltage responses can be measured for 0.1-1 seconds long. The \( \sigma_{app}(t) \) plot for the coplanar responses exhibits three parameters equally as well as for the coaxial responses.

Like it was the case in the coaxial geometry, it is also true for the coplanar responses that the early time apparent conductivity \( \sigma_{app}(t \rightarrow 0) \) is the conductivity of the local layer \( \sigma_1 \) where the tool is located. Conversely, the layer conductivity can be measured easily by the apparent conductivity at earlier times.

The late time apparent conductivity \( \sigma_{app}(t \rightarrow \infty) \) is some average of conductivities of both layers. The conclusions derived for the coaxial responses apply equally well to the coplanar responses. However, the value of the late time conductivity for the coplanar responses is not the same as for the coaxial responses. For coaxial responses, the late time conductivity is close to the arithmetic average of two-layer conductivities in two-layer models.

Fig. 32 shows the late time conductivity \( \sigma_{app}(t \rightarrow \infty) \) for coplanar responses obtained as from the model calculations (line 77) whereby D=50 m and L=1 m, but for different conductivities of the local layer while the target conductivity is fixed at 1 S/m. Late time conductivity is determined by the local layer conductivity, and is numerically close to the square root average as,

\[
\sqrt{\sigma_{app}(t \rightarrow \infty)} = \frac{\sqrt{\sigma_1} + \sqrt{\sigma_2}}{2},
\]

as is shown by line 78 in Fig. 32.

To summarize, the late time conductivity \( \sigma_{app}(t \rightarrow \infty) \) can be used to estimate the conductivity of the adjacent layer \( \sigma_2 \) when the local conductivity near the tool \( \sigma_1 \) is known, for instance, from the early time conductivity \( \sigma_{app}(t \rightarrow 0) = \sigma_1 \). This is illustrated in Fig. 33 wherein line 79 has been obtained from model calculations and line 79 displays the average approximation.

Estimation of the Distance (D) to the Electromagnetic Anomaly

The transition time \( t_d \), at which the apparent conductivity starts deviating from the local conductivity \( \sigma_1 \) toward the late time conductivity clearly depends on the distance (D) of the tool 80 (e.g. the transmitter T) to the bed boundary 85, as shown in Fig. 30.

The transition time \( t_d \) may be defined by the time at which the \( \sigma_{app}(t) \) cuts the cutoff conductivity \( \epsilon \), that is, in this example, the arithmetic average between the early time and the late time conductivities:

\[
\sigma_{app}(t \rightarrow 0) = \frac{\sigma_1 + \sigma_2}{2}.
\]

The transition time \( t_d \) is dictated by the ray-path, \( D \) minus \( L/2 \) that is, half the distance of the EM signal to travel from the transmitter to the bed boundary to the receiver, independently of the resistivity of the two layers.

Conversely, the distance (D) can be estimated from the transition time \( t_d \), as shown in Fig. 34, where \( L=1 \) m.

Analysis of Transient Electromagnetic Response Data for Three or More Formation Layers

The next model shows a conductive near layer, a very resistive layer, and a further conductive layer. The geological configuration is depicted in Fig. 35, together with a coaxial tool 80 in a relatively conductive formation 82 wherein an anomaly is located in the form of a relatively resistive layer 83. As shown, the formation on the other side of layer 83, as seen from tool 80 and identified in Fig. 35 by reference numeral 84, is identical to the formation 82 on the tool side of the layer 83. However, the method will also work if the formation 84 on the other side of layer 83 would constitute a layer that has different properties from those of the near formation 82.

In either case, the tool “sees” the anomaly 83 as a first layer at a first distance \( D_1 \) away and having a thickness \( \Delta \), and it “sees” the formation on the other side of the anomaly 83 as a second layer \( D_4 \) at a second distance \( D_3 = D_2 + \Delta \) away and having infinite thickness. Fig. 36 is a graph showing calculated apparent resistivity response \( R_{app} \) versus time \( t \) for a geometry as given in Fig. 35. For the calculation of Fig. 36, it has been assumed that the anomaly is formed of a resistive salt bed, having a resistivity of 100 \( \Omega \), and that the formation is formed of for instance a brine-saturated formation having a resistivity of 1 \( \Omega \). The tool has been modeled as being oriented with its main axis parallel to the first interface 81 between the brine-saturated formation 82, and the distance between the main axis and the first layer 83, \( D_1 \), has been taken 10 m. The resistive bed thickness \( \Delta \) has been varied from a fraction of a to 100 meters in thickness.

The first climb of \( R_{app}(t) \) is the response to the salt and takes place at \( 10^{-5} \) s with an \( L=1 \) m tool when the salt is at \( D_1 = 10 \) m away. If the salt is fully resolved (by infinitely thick salt beyond \( D_1 = 10 \) m), the apparent resistivity should read 3 \( \Omega \) m asymptotically. The subsequent decline of \( R_{app}(t) \) is the response to a conductive formation behind the salt (resistive bed). \( R_{app}(\text{late } t) \) is a function of conductive bed resistivity and salt thickness. If the time measurement is limited to \( 10^{-7} \) s, the decline of \( R_{app}(t) \) may not be detected for the salt thicker than 500 m.

With respect to the resistive bed resolution, the coaxial responds to a thin (1-2 m thick) bed. The time at which \( R_{app}(t) \) peaks or begins declining depends on the distance to the conductive bed behind the salt. As noted previously, when plotted in terms of apparent conductivity \( \sigma_{app}(t) \), the transition time may be used to determine the distance to the boundary beds.

Another three-layer formation was also modeled, as shown in Fig. 37. In this instance, the intermediate layer 83 was a more conductive layer than the surrounding formation 82. This conductive bed 83 may be considered representative of, for instance, a shale layer. The coaxial tool 80, having an \( L=1 \) m spacing, is located in a borehole in a formation 82 having a resistivity of 10 \( \Omega \), and is located \( D_1 = 10 \) m from the less resistive (more conductive) layer 83, which has a resistivity of 1 \( \Omega \). The third layer 84 is beyond
the conductive bed 83 and has a resistivity of 10 Ωm as does layer 82. The conductive bed 83 was modeled for a range of thicknesses Δ varying from fractions of a meter up to an infinite thickness. The apparent resistivity, as calculated, is set forth in FIG. 38.

The decrease in $R_{app}(t)$, which can be seen in FIG. 38, is attributed to the presence of the shale (conductive) layer and appearances as $t \rightarrow 10^{-3}$ s. The shale response is fully resolved by an infinitely thick conductive layer that approaches 3 Ωm. The subsequent rise in $R_{app}(t)$ is in response to the resistive formation 84 beyond the shale layer 83. The transition time is utilized to determine the distance $D_1$ from the tool 80 to the interface 85 between the second and third layers (83 respectively 84). $R_{app}(late \ t)$ is a function of conductive bed resistivity. As the conductive bed thickness Δ increases, the time measurement must likewise be increased ($>10^{-2}$ s) in order to measure the rise of $R_{app}(t)$ for conductive layers thicker than 100 m.

Still another three-layer model is set forth in FIG. 39, wherein the coaxial tool 80 is in a conductive formation 82 (1 Ωm), and a highly resistive second layer 84 (100 Ωm) as might be found in, for instance, a salt dome. Formation 82 and the second layer 84 are separated by a first layer 83 that has an intermediate resistivity (10 Ωm). The thickness Δ has been varied in the calculations of the apparent resistivity response, as depicted in FIG. 40.

The response to the intermediate resistive layer is seen at $10^{-3}$ s, where $R_{app}(t)$ increases. If the first layer 83 is fully resolved by an infinitely thick bed, the apparent resistivity approaches a 2.6 Ωm asymptote. As noted in FIG. 40, the $R_{app}(t)$ undergoes a second stage increase in response to the 100 Ωm highly resistive second layer 84. Based on the transition time, the distance to the interface is determined to be 110 m.

Though complex, the apparent resistivity or apparent conductivity in the above examples delineates the presence of multiple layers. The observed changes of apparent conductivity (or apparent resistivity) allow determination of the distances $D_1$ and $D_2$.

Transient Electromagnetic Responses Involving Formation Anisotropy

As stated above, an electromagnetic anomaly may display anisotropic electromagnetic properties. An example is shown in FIG. 6, if $R_\perp \neq R_\|$. Various mechanisms may give rise to a macroscopic electromagnetic induction effect. For instance, oriented fractures may generate an anisotropic response. Electromagnetic anisotropy may also arise intrinsically in certain types of formations, such as shales, of may arise as a result of sequences of relatively thin layers.

In the way as depicted in FIG. 6, the principal anisotropy direction corresponds to the approach angle θ. This correspondence is mainly for reasons of simplicity in setting forth the embodiments, and need not necessarily be the case in every situation within the scope of the invention.

In the following it will be explained how electromagnetic anisotropy of at least one of the formation layers may be taken into account when analyzing time-dependent transient response signals. This may comprise determining one or more anisotropy parameters that characterize the anisotropic electromagnetic properties. Amongst anisotropy parameters are anisotropy ratio $\alpha$, anisotropic factor $\beta$, conductivity along a principal anisotropy axis $\sigma_\|$, or resistivity along a principal anisotropy axis $\sigma_\perp$ (or resistivity in a plane perpendicular to the principal anisotropy axis $\sigma_\perp$). tool axis angle relative to the principal anisotropy axis.

Using the concepts of apparent conductivity or apparent resistivity and/or apparent dip or azimuth, the distance and/or direction to an anomaly may be determined from the time-dependent transient response signals when the anomaly, and/or a distant formation layer, comprise(s) an electromagnetic anisotropy or when the transmitter and/or receiver antennae are embedded in an anisotropic formation layer.

Using the principles set forth above, the analysis taking into account anisotropy may be extended to multiple bedded formations, including those where only a distant formation layer or target anomaly gives anisotropic electromagnetic induction responses (such as for instance in FIG. 6) or where a local formation layer wherein the transmitter and receiver antennae are located, displays anisotropic behavior and one or more other, isotropic or anisotropic layers are present at a distance. The distance and direction from the tool to the more distant layers and/or the target anomaly may then be determined, provided that anisotropy is taken into account.

In the forthcoming explanation, for reasons of simplicity, it will be assumed that the anisotropy has a vertically aligned principal axis, such that the angle between the tool axis $z$ and the principal anisotropy axis corresponds to the dip angle or deviation angle $\theta$. The term horizontal resistivity $R_\perp$ may be employed, which generically corresponds to the resistivity in the anisotropy plane perpendicular to the principal anisotropy direction. The term vertical resistivity $R_\|$ generally refers to resistivity in the principal anisotropy direction or normal direction.

Transient EM Responses in a Homogeneous Anisotropic Formation

Considered is an anisotropic formation, in which a vertical resistivity $R_\perp$ (or its inverse vertical conductivity $\sigma_\perp$) is different from the horizontal resistivity $R_\|$ (or horizontal conductivity $\sigma_\|$). Assumed is that the formation is azimuth-symmetric, in the horizontal direction. The tool axis $z$ is deviated from the vertical direction by the dip (deviation) angle $\theta$ in the $xz$-plane. The transmitter antenna is placed at origin. The receiver antenna is placed at $(x = L \sin \theta, y = 0, z = L \cos \theta)$. There may be four independent combinations of transmitter and receiver orientations that render non-zero responses.

In addition to a coaxial response, $V_{xz}$, there are two coplanar responses, $V_{xy}$ and $V_{yz}$, and one cross-component response $V_{xy} = V_{yz}$. One coplanar response, $V_{xy}$, is from a transverse transmitter antenna and receiver antenna that are oriented within the $xz$-plane. Another coplanar response, $V_{yz}$, is from a transverse transmitter and receiver both of which are oriented in the $y$-axis direction. The cross-component response is from a transverse receiver antenna with the longitudinally oriented transmitter antenna, or vice versa. The transverse receiver antenna is directed within the $xz$-plane. Any cross-component involving either a transmitter or a receiver oriented in the $y$-axis direction, i.e. $V_{xy}$ and $V_{yz}$ and $V_{xz}$ are all vanishing.

The above has been set forth in tool-coordinates. It is further remarked that any antenna that is sensitive to a
transverse component of an electromagnetic induction field suffices as a transverse antenna. 

Applicants have derived the transient response in time domain, expressed in terms of horizontal conductivity \( \sigma_{h} \) and anisotropic factor \( \beta \), are given by:

\[
V_{z}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ \frac{1}{4} \left( \beta^{2} e^{-2t} (e^{\beta t} + 1) - 1 \right) \right\};
\]

\[
V_{x}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ \frac{1}{4} \left( \beta^{2} e^{-2t} (e^{\beta t} + 1) - 1 \right) \right\};
\]

\[
V_{y}(t) = V_{z}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ \frac{1}{4} \left( \beta^{2} e^{-2t} (e^{\beta t} + 1) - 1 \right) \right\};
\]

\[
V_{y}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ \frac{1}{4} \left( \beta^{2} e^{-2t} (e^{\beta t} + 1) - 1 \right) \right\};
\]

\[
V_{x}(t) = = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ \frac{1}{4} \left( \beta^{2} e^{-2t} (e^{\beta t} + 1) - 1 \right) \right\};
\]

In these equations, \( \sigma_{h} \) and \( C \) is a constant. The anisotropic factor \( \beta \) is defined as:

\[
\beta = \sqrt{1 + (a^{2} - 1)\sin^{2} \theta};
\]

\[
\sigma_{h}^{2} = \frac{\sigma_{v}}{\sigma_{h}^{2}}.
\]

The following remarks may be made based on these equations:

1. The coaxial response depends only on the horizontal resistivity \( R_{h} = 1/\sigma_{h} \) and the anisotropic factor \( \beta \) that is determined by the anisotropy ratio \( \alpha^{2} = \sigma_{y}/\sigma_{h} = R_{y}/R_{h} \), and the dip angle \( \theta \). Conversely, neither the anisotropy nor the dip angle can be determined from coaxial measurements alone.

2. Both coplanar responses depend on the horizontal resistivity, the anisotropic factor, and the dip angle.

3. In vertical boreholes with \( \theta = 0 \), the coaxial response depends only on the horizontal resistivity, while the coplanar response is determined by both the horizontal resistivity and the vertical resistivity.

4. In horizontal logging with \( \theta = \pi/2 \), the coaxial response depends on both the horizontal resistivity and the vertical resistivity, but the coplanar response is determined solely by the horizontal resistivity.

5. Because \( u^{2} \to 0 \) as \( t \to \infty \), the dip angle is determined by:

\[
\frac{2V_{x}(t)}{V_{x}(t) - V_{z}(t)} = \tan 2\theta + O(u^{2}),
\]

whereby \( O(u^{2}) \) denotes a remainder on the order of \( u^{2} \).

Late Time Responses in a Homogeneous Anisotropic Formation

Similar to the investigation set forth above with regard to layer models, the late time limits may be derived. As \( t \to \infty, u^{2} \to 0 \), and therefore these limits converge. Taking into account anisotropy, the late time limits of equations (41) to (44) are:

\[
V_{z}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ 1 + (a^{2} - 1)\sin^{2} \theta \right\};
\]

\[
V_{x}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ 1 + (a^{2} - 1)\cos^{2} \theta \right\};
\]

\[
V_{y}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ 1 + (a^{2} - 1)\cos^{2}\sin^{2} \theta \right\};
\]

\[
V_{x}(t) = C \frac{(\mu_{0} \sigma_{h} / \beta)^{1/2}}{8 \pi^{3/2}} e^{-2t} \left\{ 1 + (a^{2} - 1) \right\};
\]

The dip (deviation) angle is determined by:

\[
\theta = \tan^{-1} \frac{V_{y}(t)}{V_{x}(t) - V_{z}(t)}.
\]

The anisotropy ratio \( \alpha^{2} \) may be determined from:

\[
\frac{V_{z}(t) \to \infty + V_{x}(t) \to \infty}{2V_{y}(t) \to \infty} = 1 + \frac{3}{4}(a^{2} - 1).
\]

When the dip angle \( \theta \) is known or estimated, the anisotropy ratio may alternatively be determined from:

\[
\frac{V_{x}(t) \to \infty - V_{z}(t) \to \infty}{V_{x}(t) \to \infty + V_{z}(t) \to \infty} = \frac{3}{2 + \frac{3}{4}(a^{2} - 1)} \cos2\theta.
\]
It is further remarked that the sum of the co-axial response with the Xx coplanar response is independent from the approach angle.

Apparent Conductivity For Co-Axial and Co-Planar Responses in a Homogeneous Anisotropic Formation

Similar to the investigation set forth above with regard to layer models, apparent conductivity is also a useful derived formation quantity in case of an anisotropic formation layer.

The apparent conductivity is defined for both coaxial ($\sigma_{\text{ax}}(t)$) and coplanar ($\sigma_{\text{xy}}(t)$) responses. The apparent conductivity is the time-varying conductivity that would give the measured coaxial or coplanar response at time $t$ if the formation would be homogeneous and isotropic.

As before, the time-changing apparent conductivities depend on the voltage response in a coaxial tool ($V_{\text{ax}}(t)$) or in a coplanar tool ($V_{\text{xy}}(t)$) at each time of measurement as:

$$V_{\text{ax}}(t) = \frac{I(t) \sigma_{\text{ax}}(t)}{8 \pi r^2} e^{-t^2};$$

$$V_{\text{xy}}(t) = \frac{I(t) \sigma_{\text{xy}}(t)}{8 \pi r^2} (1 - t^2) e^{-t^2};$$

wherein

$$t^2 = \frac{\mu_0 \sigma_{\text{xy}}(t)}{4 I}; \quad \sigma_{\text{xy}}(t)$$

Then, at large $t$, the apparent conductivity approaches the value determined by the anisotropic conductivity and the dip angle as follows:

$$\sigma_{\text{ax}}(t \to \text{large}) = \sigma_{\text{r}} \left(1 + \frac{3}{4}(\sigma^2 - 1) \sin^2 \theta\right)^{\frac{3}{2}} \text{ for coaxial response;}$$

$$\sigma_{\text{xy}}(t \to \text{large}) = \sigma_{\text{r}} \left(1 + \frac{3}{4}(\sigma^2 - 1) \cos^2 \theta\right)^{\frac{3}{2}} \text{ for Xx-coplanar response;}$$

$$\sigma_{\text{xy}}(t \to \text{large}) = \sigma_{\text{r}} \left(1 + \frac{3}{4}(\sigma^2 - 1) \cos \theta\right)^{\frac{3}{2}} \text{ for Yy-coplanar response.}$$

In terms of the apparent conductivity,

$$\sigma_{\text{ax}}(t) \left|_{\text{large}} = \sigma_{\text{r}} \left(2 + \frac{3}{4}(\sigma^2 - 1)\right); \text{ and}

\sigma_{\text{xy}}(t) \left|_{\text{large}} = \sigma_{\text{r}} \left(2 + \frac{3}{4}(\sigma^2 - 1) \cos 2\theta\right).$$

The anisotropy ratio $\sigma^2$ may be estimated from the ratio of equations (61) and (60), and the estimated $\theta$ as:

$$\frac{\sigma_{\text{ax}}(t) \left|_{\text{large}} - \sigma_{\text{xy}}(t) \left|_{\text{large}}}{\sigma_{\text{ax}}(t) \left|_{\text{large}} + \sigma_{\text{xy}}(t) \left|_{\text{large}} = \frac{3}{2}(\sigma^2 - 1)}{2 + \frac{3}{4}(\sigma^2 - 1)} \cos 2\theta.}$$

MODELING EXAMPLES

FIGS. 41 to 45 relate to transient electromagnetic induction measurements, and analysis thereof, in a homogeneous anisotropic formation for various $\beta^2$ (in order of increasing anisotropy: 1.0; 0.8; 0.6; 0.4; 0.3) for a coaxial $L=1$ m tool.

Of these Figures, FIG. 41 shows the calculated coaxial voltage responses for a formation wherein the conductivity in horizontal direction $\sigma_{\text{H}}=1$ S/m ($R_{\text{H}}=1$ $\Omega$m). The lines show the voltage response as a function of time $t$ (ranging from 1E-08 sec to 1E+00 sec on a logarithmic scale) after a step-wise sudden switching off of the transmitter. Line 101 corresponds to a homogeneous isotropic formation ($\beta^2=1.0$) and should ideally correspond to a dipole solution. Lines 102, 103, 104, and 105 represent increasing anisotropy and respectively correspond to $\beta^2=0.8$, $\beta^2=0.6$, $\beta^2=0.4$, and $\beta^2=0.3$.

FIG. 42 shows the apparent conductivity that has been calculated from the responses as shown in FIG. 41. The same line numbers have been used as in FIG. 41.

FIG. 43 is similar to FIG. 42 but it shows the apparent conductivity that has been derived from responses calculated for formations with $\sigma_{\text{r}}=0.1$ S/m ($R_{\text{r}}=10$ $\Omega$m). The same general behavior is found.

FIG. 44 is similar to FIGS. 42 and 43, but it shows the apparent conductivity that has been derived from responses calculated for formations with $\sigma_{\text{r}}=0.01$ S/m ($R_{\text{r}}=100$ $\Omega$m). The same general behavior is again found.

In each of FIGS. 42, 43, and 44, the late time apparent conductivity is constant for each of the anisotropic factors, indicative of a macroscopically homogeneous formation. The late time apparent conductivity decreases with anisotropic factor as is expected because the vertical conductivity, along the principal axis of the anisotropy, is lower than the horizontal conductivity.

FIG. 45 plots the late time asymptotic value of coaxial apparent conductivity $\sigma_{\text{ax}}(t \to \infty)$ over $\sigma_{\text{r}}$ against

$$(1 + \frac{3}{4}(\beta^2 - 1))^2 \beta.$$ The resulting straight line demonstrates the linear relationship. When taking into account the anisotropy, the correct value of the horizontal formation resistivity (or conductivity) can thus be extracted from the asymptotic coaxial apparent conductivity values.

Even for highly anisotropic formations, the apparent conductivity is almost indistinguishable from apparent conductivity of a homogeneous isotropic formation with a lower conductivity. Interpretation mistakes may thus easily be made if anisotropy is not taken into account when analyzing.
As follows from the above, anisotropy can be taken into account, for instance by combining coaxial responses with coplanar responses. The precise embodiment depends on which of the parameters are known or estimated. The sum of the coaxial response with the Xx coplanar response is independent from the approach angle. If C and $\sigma_y$ are known or estimated then the anisotropy ratio $\alpha^2$ follows from the late time value of sum $V_x N_x V_x N_y$. If, on the other hand, the approach angle is known, C and $\sigma_y$ don’t need to be known because the anisotropy ratio $\alpha^2$ may be derived from Eq. (53). If none of the other parameters is known, Eq. (52) may be employed requiring combining coaxial response with two independent coplanar responses.

Apparent Dip in a Homogeneous Anisotropic Formation

In FIG. 46, apparent dip angles $\theta_{app}(t)$ derived using Eq. (51) from calculated coaxial, coplanar and cross-component transient responses from a L = 1 m tool in a formation of $R_{xy}/10 \Omega m$ and $R_{xy}/R_{xy}-9$, for various approach angles, or dip angles. Line 106 corresponds to 0–30°; line 107 to 45–60°; line 108 to 60–60°; and line 109 to 75°. The dip angle is thus reflected accurately by the asymptotic value of the apparent dip. The asymptotic value is reached in approximately 1E-06 sec.

Apparent Resistivity for Co-Axial and Co-Planar Responses in a Formation Layer Comprising Multiple Sub-Layers

FIG. 47 shows an electromagnetic induction tool 80 in a formation layer 110 comprising a sequence or package of alternating sets of sub-layers 112 and 114, set 112 having electromagnetic properties, notably conductivity, that is different from that set 114. The tool axis is depicted in the plane of the sub-layers. While each sub-layer in the laminate of thin layers may have isotropic properties such as isotropic conductivity, the combined effect of the sub-layers may be that the formation layer that consists of the sub-layers exhibits an anisotropic electromagnetic induction. If each sub-layer 112, 114 in the formation layer 110 acts as an individual resistor, the macroscopic resistivity (inverse of conductivity) of the formation layer in a planar direction may be a resultant of all the layer-resistors in parallel while the macroscopic resistivity in a normal direction (i.e., perpendicular to the layers) may be a resultant of all the layer resistors in series. In equation form:

$$ R_k = \frac{1}{\Delta_k} \int_0^\infty R_k(\omega) d\omega $$

for the resistivity in the vertical, or principal direction, and

$$ \sigma_n = \frac{1}{\Delta_n} \int_0^\infty \sigma_n(\omega) d\omega $$

for the conductivity in the horizontal, or in-plane, direction perpendicular to the principal direction. Of course, $\sigma_n$ can be found using $\sigma_n = 1/R_n$, and $R_k$ can be found using $R_k = 1/\sigma_k$. Hence the in-plane resistivity is typically lower than the resistivity in the principal direction. These equations also hold for more general cases whereby the sub-layers are not of equal thickness and/or the sublayers are not of equal conductivity.

FIG. 48 shows the calculated apparent resistivity for the tool in the geometry of FIG. 47, whereby L = 1 m, the resistivity of sub-layers 112 is 10 $\Omega m$, the resistivity of sub-layers 114 is 1 $\Omega m$, and each sub-layer is 10 m of thickness. Line 115 corresponds to apparent resistivity for co-axial measurement geometry while line 116 corresponds to apparent resistivity for co-planar measurement geometry.

The apparent resistivity represented by lines 115 and 116 reflect the near-later resistivity of 1 $\Omega m$ at short times after the switching off of the transmitter. After a time span of approximately 2E-5 sec, the apparent resistivity starts to increase due to the higher resistivity of 10 $\Omega m$ in the first adjacent sub-layers 112. So far, the apparent resistivity reflects what was set forth above for formations comprising two or three isotropic formation layers.

However, for later times the sub-layers are no longer individually resolved in the responses, in which case apparent resistivity is believed to reflect contributions from the sub-layer where the tool 80 is located, the adjacent layers and next adjacent layers, and so on. Effectively, the transient responses will show the macroscopic anisotropic behavior. In the example of FIG. 48, the collection of the isotropic sub-layers that are not individually resolved in the transient responses are described by assuming an anisotropic layer with an anisotropic ratio of $\alpha = R_{xy}/R_{xy}$=1/(0.555.5) 0.33, which can be found out using the late time apparent resistivities as set forth above for the homogeneous anisotropic formation. It may be better to invert the responses assuming a homogenous anisotropy than to try and determine the individual sub-layer structure.

The dotted lines 117 and 118 in FIG. 48, which correspond to the co-axial and co-planar apparent conductivities calculated for $R_{xy} = 1.82$ (i.e. 1/0.55) $\Omega m$ and $R_{xy} = 5.5$ $\Omega m$, indeed match the drawn lines 115 and 116 well, at large t.

The combined, “macroscopic,” anisotropic effect of a sub-layered anomaly, such as is shown in FIG. 49, may also be observed. Here, the anomaly A is formed of a formation layer having a thickness $\Delta$ comprising a thinly laminated sequence of a first formation material $A_1$ and a second formation material $A_2$. FIG. 49 also indicates coaxial 60, coplanar 62, and cross-component 64 measurement arrangements, wherein a transmitter coil T and a receiver coil R are spaced a distance L apart from each other. The distance between the transmitter coil T and the nearest interface 55 between the near formation layer and the anomaly A is indicated by $D_1$.

Using the principles set forth above, the analysis taking into account anisotropy may be extended to multiple bedded formations, including those where only a distant formation layer displays macroscopic electromagnetic induction responses (such as for instance in FIG. 49) or where a local formation layer wherein the transmitter and receiver antennae are located, displays anisotropic behavior but whereby one or more other, isotropic or anisotropic layers are present at a distance.

Geosteering Applications

As stated before in this specification, electromagnetic anisotropy may arise intrinsically in certain types of formations, such as shales. A shale may cap a reservoir of mineral hydrocarbon fluids. It would thus be beneficial to precisely locate a shale during drilling of a well, and drill between for instance 10 m and 100 m below the shale to
enable optimal production of the hydrocarbon fluids from the reservoir. This can be done either by traversing the shale or steering below the shale in a deviated well such as a horizontal section.

In other cases, the hydrocarbon containing reservoir may have materialized in the form of a stack of thin sands, which itself may exhibit anisotropic electromagnetic properties. It would be beneficial to identify the presence of such sands and steer the drilling bit into these sands.

In each of these cases, geosteering may be accomplished by performing the transient electromagnetic analysis while drilling and taking into account formation anisotropy. This may be implemented using the system as schematically depicted in FIG. 1A.

More generally, geosteering decisions may be taken based on locating any type of electromagnetic anomaly using transient electromagnetic responses. Such geosteering applications allow to more accurately locate hydrocarbon fluid containing reservoirs and to more accurately drill into such reservoirs allowing to produce hydrocarbon fluids from the reservoirs with a minimum of water.

In order to produce the mineral hydrocarbon fluid from an earth formation, a well bore may be drilled with a method comprising the steps of:

-suspending a drill string in the earth formation, the drill string comprising at least a drill bit and measurement sub comprising a transmitter antenna and a receiver antenna;
-drilling a well bore in the earth formation;
-inducing an electromagnetic field in the earth formation employing the transmitter antenna;
-detecting a transient electromagnetic response from the electromagnetic field, employing the receiver antenna;
-deriving a geosteering cue from the electromagnetic response.

Drilling of the well bore may then be continued in accordance with the geosteering cue until a reservoir containing the hydrocarbon fluid is reached.

Once the well bore extends into the reservoir containing the mineral hydrocarbon fluid, the well bore may be completed in any conventional way and the mineral hydrocarbon fluid may be produced via the well bore.

Geosteering may be based on locating an electromagnetic anomaly in the earth formation by analysing the transient response in accordance with the present specification, and taking a drilling decision based on the location relative to the measurement sub. The location of the anomaly may be expressed in terms of distance and/or direction from the measurement sub to the anomaly.

To facilitate executing the drilling decision, the drill string may comprise a steerable drilling system 19, as shown in FIG. 1A. The drilling decision may comprise controlling the direction of drilling, e.g. by utilizing the steering system 19 if provided, and/or establishing the remaining distance to be drilled.

Accordingly, the geosteering cue may comprise information reflecting distance between the target ahead of the bit and the bit, and/or direction from the bit to target. Distance and direction from the bit to the target may be calculated from the distance and direction from the tool to the bit, provided that the bit has a known location relative to the electromagnetic measurement tool.

Transient electromagnetic induction data may be correlated with the presence of a mineral hydrocarbon fluid containing reservoir, either directly by establishing conductivity values for the reservoir or indirectly by establishing quantitative information on formation layers that typically surround a mineral hydrocarbon fluid containing reservoir.

In preferred embodiments, the transient electromagnetic induction data, processed in accordance with the above, is used to decide where to drill the well bore and/or what is its preferred path or trajectory. For instance, one may want to stay clear from faults. Instead of that, or in addition to that, it may be desirable to deviate from true vertical drilling and/or to steer into the reservoir at the correct depth.

The distance from the measurement sub to an anomaly in the formation may be determined from the time in which one of apparent conductivity and apparent resistivity begins to deviate from the corresponding one of conductivity and resistivity of formation in which the measurement sub is located and/or determining time in which one of apparent dip and apparent azimuth and cross-component response starts to deviate from zero. The distance may also be determined from when one of apparent dip and apparent azimuth reaches an asymptotic value.

The electromagnetic anomaly may be located using at least one of time-dependent apparent conductivity, time dependent apparent resistivity, time-dependent dip angle, and time-dependent azimuth angle from the time dependence of the transient response, in accordance with the disclosure elsewhere hereinabove.

Any of the above mentioned time-dependencies can provide a useful geosteering cue.

Fast Imaging Utilizing Apparent Conductivity and Apparent Angle

Apparent conductivity and apparent dip may also be used to create an "image" or representation of the formation features. This is accomplished by collecting transient apparent conductivity data at different positions within the borehole.

The apparent conductivity should be constant and equal to the formation conductivity in a homogeneous formation. The deviation from a constant conductivity value at time (t) suggests the presence of a conductivity anomaly in the region specified by time (t). The collected data may be used to create an image of the formation relative to the tool.

When the apparent resistivity plots (\(R_{app}(z, t)\)) or apparent conductivity plots (\(\sigma_{app}(z, t)\)) at different tool positions are arranged together to form a plot in both z- and t-coordinates, the whole plot may be used as an image log to view the formation geometry, even if the layer resistivity may not be immediately accurately determined.

An example of such an image representation of the transient data as shown in FIG. 50 for a L=1 coaxial tool. The z coordinate references the tool depth along the borehole. The \(\sigma_{app}(z, t)\) plot shows the approaching bed boundary as the tool moves along the borehole.

FIG. 51 shows another example. The z-coordinate represents the tool depth along the borehole with the borehole intersecting the layer boundary in this case. The \(R_{app}(z, t)\) plot clearly helps to visualize the approaching and crossing the bed boundary as the tool moves along the borehole, for instance during drilling of the borehole.

Another example is shown in FIG. 52 wherein a 3-layer model is used in conjunction with a coaxial tool having a 1 m spacing and is in two differing positions in the formation. The results are plotted on FIG. 53A, where the
apparent resistivity $R_{app}(t)$ is plotted at various points as the coaxial tool 80 approaches the resistive layer (see FIG. 53B).

[0277] FIG. 53A may be compared to FIG. 53B to discern the formation features. Starting in the 10 Ωm layer 82, the drop in $R_{app}(t)$ is attributable to the 1 Ωm layer 83 and the subsequent increase in $R_{app}(t)$ is attributable to the 100 Ωm layer 84. Curves (91, 92, 93) may readily be fitted to the deflection points to identify the responses to the various beds, effectively imaging the formation. Line 91 corresponds to the deflection points caused by the 1 Ωm bed 83, line 92 to the salt 84, and line 93 to the deflection points caused by 10 Ωm bed 82. Moreover, the 1 Ωm curve may be readily attributable to direct signal pick up between the transmitter and receiver when the tool is located in the 1 Ωm bed.

[0278] In still another example, the apparent dip $\theta_{app}(t)$ may be used to generate an image log. In FIG. 54A a coaxial tool is seen as approaching a highly resistive formation at a dip angle of approximately 30 degrees. The apparent dip response is shown in FIG. 54B. As noted previously, the time at which the apparent dip response occurs is indicative of the distance to the formation. When the responses for different distances are plotted together, a curve may be drawn indicative of the response as the tool approaches the bed, as shown in FIG. 54B.

[0279] Summarising, the subterranean formation traversed by a wellbore may be imaged using a tool comprising a transmitter for transmitting electromagnetic signals through the formation and a receiver for detecting response signals in a procedure comprising steps wherein

[0280] [0281] the tool is brought to a first position inside the wellbore;

[0282] the transmitter is energized to propagate an electromagnetic signal into the formation;

[0283] a response signal that has propagated through the formation is detected;

[0284] a derived quantity is calculated for the formation based on the detected response signal for the formation;

[0285] the derived quantity for the formation is plotted against time.

Then the tool is moved to at least one other position within the wellbore, whereafter the steps set out above are repeated. Optionally, this can be done again. Then an image of the formation within the subterranean formation is created based on the plots of the derived quantity.

[0286] Optionally tool is then again moved to at least one more position within the wellbore and the whole procedure can be repeated again.

[0287] Creating the image of the formation features may include identifying one or more deflection points on each plotted derived quantity and fitting a curve to the one or more deflection points.

[0288] Thus an image of the formation may be created using apparent conductivity/resistivity and apparent dip angle without the additional processing required for inversion and extraction of information. This information is capable of providing geosteering queues as well as the ability to profile subterranean formations.

1. A method of analyzing a subterranean formation traversed by a wellbore, using a tool comprising a transmitter antenna and a receiver antenna, the subterranean formation comprising one or more formation layers and the method comprising:

- suspending the tool inside the wellbore;
- inducing one or more electromagnetic fields in the formation;
- detecting one or more time-dependent transient response signals;
- analyzing the one or more time-dependent transient response signals taking into account electromagnetic anisotropy of at least one of the formation layers.

2. The method of claim 1, wherein the at least one formation layer comprises three or more sub-layers.

3. The method of claim 2, wherein one of the three or more sub-layers has a first resistivity or conductivity that is different from a second resistivity or conductivity of another one of the three or more sub-layers.

4. The method of claim 2, wherein the sub-layers that are not individually resolved in the transient response signals jointly are approximated as one anisotropic formation layer.

5. The method of claim 1, wherein analyzing the one or more time-dependent transient response signals taking into account electromagnetic anisotropy includes deriving an anisotropy parameter of at least one formation layer from the detected one or more time-dependent transient response signals.

6. The method of claim 5, wherein the anisotropy parameter comprises at least one from a group of parameters comprising anisotropy ratio, anisotropic factor, conductivity along a principal anisotropy axis, resistivity along the principal anisotropy axis, conductivity in a plane perpendicular to the principal anisotropy axis, resistivity in a plane perpendicular to the principal anisotropy axis; tool axis angle relative to the principal anisotropy axis.

7. The method of claim 1, wherein analyzing the one or more time-dependent transient response signals comprises combining multi-axial transient measurements to derive an anisotropy parameter.

8. The method of claim 1, wherein analyzing the one or more time-dependent transient response signals taking into account electromagnetic anisotropy comprises deriving at least one of time-dependent apparent conductivity, time-dependent apparent resistivity, time-dependent dip angle, and time-dependent azimuth angle from the time dependence of the transient response signals.

9. The method of claim 1, wherein one of the formation layers comprises an anomaly, and wherein analyzing the one or more time-dependent transient response signals comprises determining at least one of a distance and a direction between the tool and the anomaly from one or more time-dependent transient response signals.

10. The method of claim 1, wherein inducing one or more electromagnetic fields in the formation comprises generating a transmission and terminating the transmission, and detecting one or more time-dependent transient response signals comprises measuring a receiver response as a function of time following the terminating the transmission.

11. A method of producing a mineral hydrocarbon fluid from an earth formation, the method comprising steps of:

- suspending a drill string in the earth formation, the drill string comprising at least a drill bit and measurement sub comprising a transmitter antenna and a receiver antenna;
- drilling a well bore in the earth formation;
- inducing an electromagnetic field in the earth formation employing the transmitter antenna;
detecting one or more time-dependent transient electromagnetic response signals from the electromagnetic field, employing the receiver antenna;

deriving a geosteering cue from the electromagnetic response;

continue drilling the well bore in accordance with the geosteering cue until a reservoir containing the hydrocarbon fluid is reached;

producing the hydrocarbon fluid.

12. The method of claim 11, wherein drilling the well bore comprises operating a steerable drilling system in the earth formation.

13. The method of claim 11, wherein inducing the electromagnetic field in the earth formation comprises generating a transmission and terminating the transmission, and detecting one or more time-dependent transient response signals comprises measuring a receiver response as a function of time following the terminating the transmission.

14. The method of claim 11, wherein deriving the geosteering cue comprises analyzing the one or more transient response signals taking into account electromagnetic anisotropy of at least one of the formation layers.

15. The method of claim 11, wherein deriving the geosteering cue comprises locating an electromagnetic anomaly in the earth formation based on the one or more time-dependent transient response signals.

16. The method of claim 15, wherein locating the electromagnetic anomaly comprises determining at least one of a distance from the measurement sub to the anomaly and a direction from the measurement sub to the anomaly.

17. The method of claim 16, wherein determining the distance comprises determining a time in which one of apparent conductivity and apparent resistivity begins to deviate from the corresponding one of conductivity and resistivity of formation in which the device is located.

18. The method of claim 16, wherein determining the distance comprises determining a time in which one of apparent dip and apparent azimuth reaches an asymptotic value.

19. The method of claim 16, wherein determining the distance comprises determining a time in which one of apparent dip and apparent azimuth and cross-component response, reaches a non-zero value.

20. The method of claim 15, wherein locating the electromagnetic anomaly comprises deriving at least one of time-dependent apparent conductivity, time dependent apparent resistivity, time-dependent dip angle, and time-dependent azimuth angle from the time dependence of the transient response.

21. The method of claim 11, wherein deriving the geosteering cue comprises deriving at least one of time-dependent apparent conductivity, time dependent apparent resistivity, time-dependent dip angle, and time-dependent azimuth angle from the time dependence of the transient response.

22. A computer readable medium storing computer readable instructions that analyze one or more detected time-dependent transient electromagnetic response signals that have been detected by a tool suspended inside a wellbore traversing a subterranean formation after inducing one or more electromagnetic fields in the formation, wherein the computer readable instructions take into account electromagnetic anisotropy of at least one formation layer in the subterranean formation.

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